Forest Research Report No. 175

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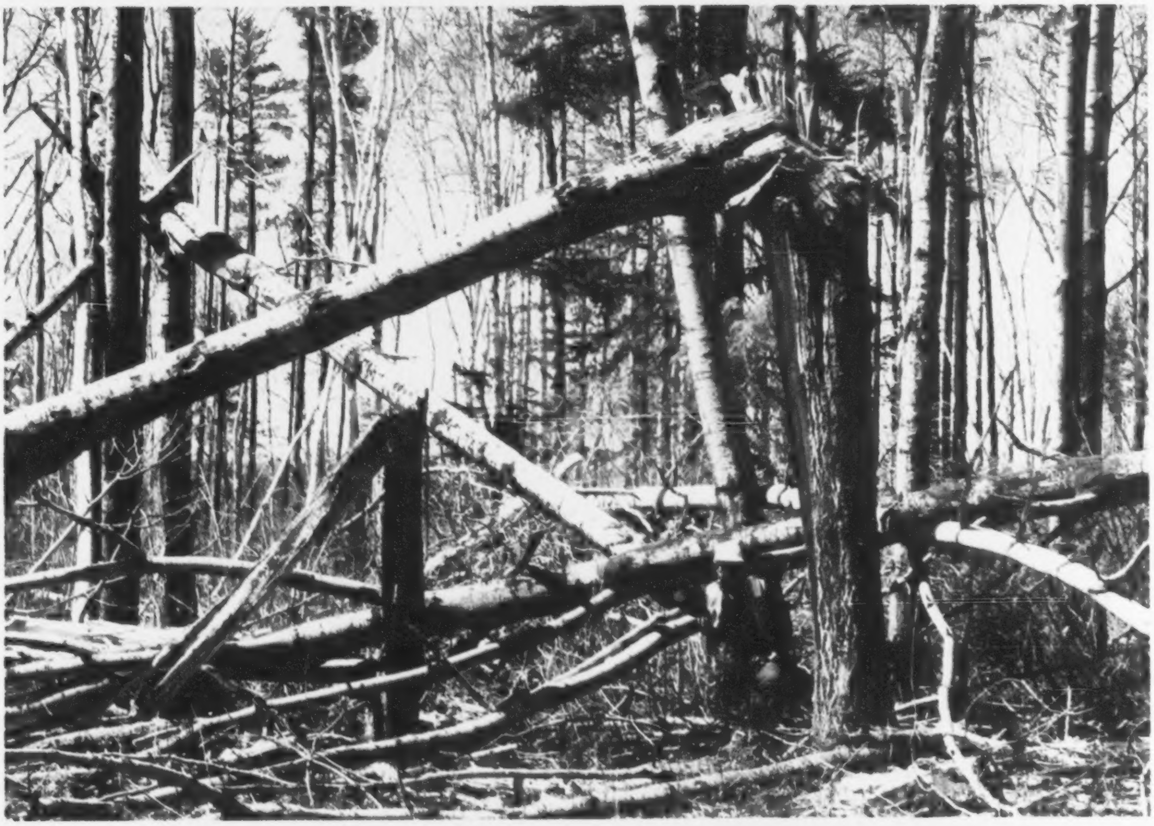

Ministry of Natural Resources

Ontario

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Abstract

A mixedwood silviculture study was established in northeastern Ontario in 2002 to test a series of innovative silvicultural treatment packages designed to create mixtures of hardwoods and conifers. One treatment package being tested included a partial harvesting treatment (50% removal in alternating 10-m-wide strips). An unharvested reference area was used as a control. After the harvesting treatment was completed, the effects of wind damage on residual overstory trees were assessed in the partially harvested and unharvested treatment areas. Those areas were monitored for 4 years to determine the amount of wind damage on residual trees and its characteristics. Wind damage was observed on the range of species and tree sizes in both treatments. While many residual overstory trees were damaged, particularly in the partially harvested plots, dead trees were more likely to be felled by wind. In this report, we document the quantity and spatial characteristics of wind damaged trees, and discuss whether, given this damage, the silvicultural objectives of the study can be achieved.

Résumé

Une étude sur la sylviculture des forêts mixtes a été menée dans le Nord-Est de l'Ontario en 2002 afin d'évaluer une série de programmes de traitements sylvicoles innovateurs destinés à la création d'un mélange de feuillus et de conifères. Un des programmes de traitement faisant parti de l'étude comprenait le traitement par récolte partielle (prélèvement de 50 % en bande alternatives de 10 m de largeur). Une zone de référence non récoltée était utilisée comme milieu témoin. Une fois les traitements de récolte terminés, les effets des dommages causés par le vent sur les étages dominants ont été évalués dans les zones de traitement partiellement récoltées et non récoltées. Ces zones ont été surveillées pendant quatre ans afin de déterminer l'ampleur et les caractéristiques des dommages causés par le vent sur les arbres résiduels. Des dommages causés par le vent ont été observés sur une variété d'espèces et de tailles d'arbres dans les deux traitements. Alors que plusieurs arbres dominants résiduels étaient endommagés, en particulier dans les lots de récoltes partielles, les arbres morts étaient plus susceptibles de tomber. Dans le présent rapport, nous documentons la quantité et les caractéristiques spatiales des arbres endommagés par le vent. De plus, nous analysons si les objectifs sylvicoles de l'étude peuvent être réalisés malgré ces dommages.

Acknowledgements

The authors are grateful for financial support from the Enhanced Forest Productivity Science fund of the Ontario Forestry Futures Trust, and the Ontario Ministry of Natural Resources (OMNR). We also thank: the SLAM study team, especially the staff at the Abitibi Bowater, Inc. office in Iroquois Falls, Ontario, for their continued interest and support; Dan MacIsaac (Canadian Wood Fibre Centre, Edmonton) and Gordon Kayahara (OMNR-Northeast Science and Information Section, South Porcupine) for their comments on an earlier draft of the report; Lisa Buse (OMNR-OFRI) for her review and editorial comments; and Shane Stuart, Dave Niblett, John Schnare, and Margie Beaudoin (OMNR-OFRI) for their technical support and field data collection.

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Introduction

In the development of silvicultural techniques to manage boreal mixedwood stands in a sustainable manner, partial harvesting operations designed to produce desired future forest conditions are an important option. However, at present forest managers have little experience in using partial harvesting techniques in the boreal forest region of Ontario and minimal knowledge of the effects of subsequent wind damage on potential to meet their forest management objectives. Increased local data and information on wind-related damage and its effects on the residual forest are needed to allow forest managers to make informed decisions about appropriate management alternatives.

Wind is a natural phenomenon in all forest landscapes and some amount of wind damage to forest stands is normal. Wind damage, sometimes referred to as blowdown, is defined as the breaking or uprooting of live trees due to strong winds (Navratil 1995). Vulnerability of individual trees and stands to wind is based on a combination of tree attributes (species, age, health, total height, crown size, rooting characteristics), stand conditions (species, density, and structure of both the candidate and surrounding stands), local topography, soils (texture, depth, soil moisture level), and predominant wind patterns (Mitchell 1995; Navratil 1995; Ruel 1995, 2000; Wang et al. 1998). Types of wind damage include windbreak, which occurs when the wind load on a tree is greater than the breaking stress of the wood, and wind throw, which occurs when wind load is less than stem strength but greater than root anchorage such that the tree does not break but rather uproots and topples (Navratil 1995). In managed stands, the amount of wind damage can influence whether silvicultural goals are met and desired future forest conditions are achieved.

Partial harvesting regimes affect many of the ecological characteristics of the stand. Changes in stand structure and density affect local light, temperature, humidity, and wind patterns, all of which affect a stand's regeneration potential. Changes to stand structure and density from partial harvesting may also make the residual stand more vulnerable to wind damage (Mitchell 1995, Ruel 1995).

In a recent Ontario Ministry of Natural Resources' annual report (OMNR 2008), clearcutting was reported as the dominant silvicultural system, applied to 88.3% of the harvested area in Ontario. Partial cutting systems (shelterwood and selection) were applied to only 11.7% of harvested area, with most of that occurring in forests in the Great Lakes-St Lawrence region. Based on the limited use of partial cutting systems in the boreal forest, uncertainty exists about the ecological and silvicultural responses of stands to these treatments. Similarly, little has been published on the rate of occurrence and effects of non-stand replacing wind damage in the eastern boreal forest.

The *Silviculture Guide to Managing Spruce, Fir, Birch, and Aspen Mixedwoods in Ontario's Boreal Forest* (OMNR 2003) outlines the province's approach to managing boreal mixedwood sites and stands. One of the management principles is the use of silvicultural practices that encourage stand development to follow natural successional pathways. Such approaches for mixedwood management and associated rationale were outlined by MacDonald (1995) and Bergeron and Harvey (1997). Managing mixedwood stands to follow natural succession pathways in boreal forests can only be achieved with the use of both partial harvest and clearcutting treatments that create desirable stand conditions for each stage of succession.

In 2002, the Stand Level Adaptive Management (SLAM) mixedwood study was established in northeastern Ontario to advance knowledge of managing boreal mixedwood forests. The primary objective of the study was to test a series of innovative silvicultural treatment packages designed to create mixtures of hardwoods and conifers while monitoring changes in ecological and silvicultural indicators of sustainability (MacDonald et al. 2003). One of the treatment packages tested included a partial harvesting component. In this treatment, a pattern of alternating 10-m-wide strips of harvested corridors and 10-m-wide unharvested corridors was applied. Corridors were oriented north-south to be perpendicular to prevailing winds and to equalize solar radiation across the harvested corridor to support regenerating conifers. The remnant corridors of residual trees were expected to provide enough shade in the harvested corridors to suppress aspen coppicing and growth while allowing the establishment and growth of planted conifer seedlings. The effectiveness of the treatment depends on the retention of residual trees over time, and this is influenced by the amount and severity of wind damage – either through wind throw or breakage.

The effects of wind damage on residual trees were monitored at the SLAM study site east of Cochrane, Ontario. The goals of this component of the study were to quantify and compare the effects of wind damage between partially harvested and unharvested portions of stands after harvest and to determine their influence on achieving the silvicultural objectives of the partial harvest treatment. Here we report the amount and distribution of wind damage in the residual stands at 1, 2, and 4 years after harvest and discuss the effects of this damage on the potential to achieve the desired silvicultural objectives. Specifically, we were interested in the effects of harvest treatments, tree species, direction of fall, stem rot, and stem form on the number and percent of wind damaged trees.

Methods

Site conditions

The study was established in 2002 in a mature, aspen-dominated mixedwood stand located in the Iroquois Falls Forest[1], east of Cochrane, Ontario (N48° 46' 40", W80° 14' 53"). The site was selected by the local forest company study partner as representative of stands where local resource managers would practice mixedwood management. It is one of two sites in the larger SLAM mixedwood study (MacDonald et al. 2003). Of the two study sites, the Cochrane study location was selected to have a wider range of parameters assessed, including wind damage impact.

Increment cores taken from dominant trees in 2002 confirmed that the stand originated in about 1920, likely after a wild fire. In 2002, the site was dominated by trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.), with lesser components of white spruce (*Picea glauca* [Moench] Voss), jack pine (*Pinus banksiana* Lamb.), balsam fir (*Abies balsamea* [L.] Mill.), black spruce (*Picea mariana* [Mill] B.S.P.) and occasional balsam poplar (*Populus balsamifera* L.) (MacDonald et al. 2003). Stocking averaged approximately 33.7 m^2 ha^{-1} in trees greater than or equal to 10 cm diameter at breast height (DBH), with hardwoods contributing 80% of the basal area and conifers 20% (MacDonald et al. 2003). Stocking of trees less than 10 cm DBH were half conifer and half hardwood. At the time of study establishment the stand was in the canopy transition stage of succession. In this successional stage, the overstory aspen and birch are reaching maturity, canopy gaps are beginning to develop, and shade tolerant species from the understory are entering the canopy (OMNR 2003).

The study area is mainly uniform with soils consisting of fresh, lacustrine clays. On the northern edge of the site, a thin to moderately thick (>50 cm) cap of fine sand or sandy loam overlies the lacustrine clay. A few isolated depressions are moister than the surrounding areas. Overall, the site and stand conditions are typical of the mixedwood forests in the area.

Harvest treatments

Within the SLAM study, the effects of a series of 4 silvicultural treatment packages intended to achieve a balanced mixture of hardwoods and conifers are being compared with an unharvested reference stand. Silviculture treatment packages were designed by a team of forest company partners and government researchers involved in the study. These treatment packages included variation on harvesting pattern, site preparation, renewal treatments, and timing and patterns of tending. Each treatment package was replicated 3 times across the study area. Details of the treatment packages relevant to this component of the study are summarized in Appendix I. A full description of all treatment packages in the SLAM study is provided by MacDonald et al (2003).

To ensure the overall study provided results representative of normal forestry operations, all operational components of the treatment packages were implemented by local contractors using conventional equipment within the forest company's regular operational schedules. Treatment plots averaging 16 to 20 ha – large enough to accommodate the company's operational standards – were established across the study area in a randomized complete block design. Within each treatment plot an intensive measurement area, designed to be approximately

[1] In 2010, the Iroquois Falls Forest was amalgamated with 3 other forests to form the Abitibi River Sustainable Forest License (SFL).

5.4 ha, was established on which data were collected for a range of silvicultural and ecological parameters. A minimum 40 m buffer of treated area existed around the intensive measurement areas. Where forest operation-related disturbances were located in a treatment plot (e.g., winter roads), those disturbed areas were excluded from any assessment. Because of this criterion, intensive measurement areas varied in size and were smaller in the partial harvest treatment plots as opposed the unharvested reference plots. Harvesting occurred in fall-winter 2002-03.

Pre- and post-harvest assessments

Pre-harvest measurements, taken in 2002 in each treatment plot, provided an indication of initial stand conditions, including stand stocking and structure, composition of ground vegetation, ecological site classification, and site productivity obtained through tree height-age relationships. During the first growing season after harvest (2003), several ecological and silvicultural characteristics were assessed at permanent sampling locations within each plot. These included vegetation dynamics, number and condition of residual overstory trees, regeneration of natural and planted trees, light characteristics within each treatment, and site meteorology (MacDonald et al. 2003).

Approximately a year after the harvesting operations, wind damage to residual trees was assessed in the intensive measurement areas in the partially harvested and unharvested reference plots. In the partial harvest treatment the area assessed for wind damage was 9.53 ha (including harvested and residual strips) and in the unharvested reference stand it was 16.70 ha.

All trees that were either uprooted (wind throw) or had a bole snapped (wind break) by wind since the time of harvest were tallied. Trees that had fallen prior to or during harvesting were not included. For each tree affected by wind in the intensive measurement areas, the following data were collected:

- Tree location: study replication, treatment plot, and UTM coordinates
- Tree attributes: species, status at time of wind damage (live/dead), DBH, tree height, crown dominance class (before damage), and crown length and width
- Damage attributes: uprooted or snapped, any evidence of any visible rot at the break/uprooted location, and direction of fall

Each assessed tree was marked with paint to help identify it in future assessments.

In the fall of 2004, approximately 2 years after harvest, wind damage was reassessed. All trees affected by wind since the previous assessment were identified and assessed using the same approach as in 2003.

To estimate pre-harvest stand and tree characteristics, we used a sub-sample of the partially harvested and unharvested treatment areas in 2005. Tallies of all live trees in 2005 were added to live trees tallied with wind damage in 2003 and 2004 within the sub-sampled area to get a more detailed estimate of total number and size of stems before harvest. Only standing or wind damaged trees >10 cm in DBH were included. For each tree species, status, DBH, total height, and crown dominance class data were collected. Approximately 0.5 ha and 0.64 ha were sampled in the partially harvested plots and unharvested reference plots, respectively. This estimate of pre-harvest conditions was used to compare to post-harvest and wind damage assessments.

From results of studies in western Canada reported by Navratil (1995), Coates (1997), and MacIsaac and Krygier (2009), most wind damage was expected to occur within the first 2 years after harvest. Based on wind damage effects observed in other research studies in Ontario, this time estimate was confirmed by a local researcher (G.B. MacDonald, MNR retired, pers. comm., 2009). Thus, the original plan was to collect only 2 years of wind damage data. However, two events led to an additional assessment. First, stands surrounding the study area were harvested using a clearcut system in the winter of 2003-04 and removal of neighbouring stands is known to influence wind patterns (Stathers et al. 1994). While a 40 m buffer was left around the intensive measurement areas to protect them from such events, concerns were raised that the intensive measurement areas might be affected. Second, and more importantly, a large wind event was recorded in November 2005 –

approximately 3 years after harvesting. During this event, gusts greater than 72 kph at a height of 4 m (unpublished data) were recorded via the on-site weather station and gusts of 83 kph were recorded at the Environment Canada weather station at the Timmins airport (closest official weather station, approximately 85 km to the southwest of the study site) (Environment Canada 2005). Due to uncertainty about whether/how these events would influence the stand, an additional assessment was conducted in the summer of 2006, approximately 4 years after the initial harvest. Protocols used in 2003 and 2004 were also applied in the 2006 assessment.

Slenderness coefficient calculations

Slenderness coefficient (SC) is an index of the stem form of a tree and can be used to assess the susceptibility of a tree to wind damage (Navratil 1995, Wang et al. 1998). It is a ratio of tree height (m) to DBH (diameter at breast height, cm). Higher SC values indicate lower tree stability and higher vulnerability to wind events. Average SCs were calculated for most wind damaged trees as well as for a sample of residual undamaged trees. SCs were not estimated for trees that could not be accurately measured (e.g., due to boles and crowns that shattered on impact during windthrow).

Data analysis

The density (stems per ha) and percent of trees (versus residual stems) damaged by wind within each harvesting treatment were calculated by species, diameter class, direction of fall, and occurrence of visible rot. Differences in percent stocking, density, or direction of fall between harvest methods, assessment years, wind damaged vs. total live trees, trees with and without visible rot, and wind damaged vs. fallen dead trees were compared using Chi square tests.

Results and Discussion

Amount of wind damage

Wind damage for the 4 years following harvest in all partially harvested and unharvested plots is summarized in Table 1. All tree species on the study site were susceptible to wind damage. Within the partially harvested plots, 6.0% of the residual trees that were live post-harvest were damaged during the 4-year assessment period. In the unharvested reference plots, 1.2% of the overstory trees were damaged in the same period. Most wind damage occurred in the first year after harvest and then in 2005-06, the year of a major wind event. Fewer trees were wind damaged in the second year after harvesting. This reduction in wind damage over time in the absence of major wind events corroborates results reported by Navratil (1995) and Coates (1997) for mixedwood stands in Alberta.

In both partially harvested and unharvested treatment plots, trembling aspen accounted for the largest number of damaged trees at 7.0 stems per ha in the partially harvested plots and 5.5 stems per ha in the unharvested reference plots. The difference is substantial, especially considering that the partially harvested area includes harvested and unharvested strips. In the partially harvested plots, many jack pine trees were also damaged; the 5.7 stems per ha represent 12.4% of the residual pine trees in these treatments post-harvest. Almost all of the jack pine occurred at the north end of the study area where soils were sand over clay, so local site conditions may have influenced their stability.

The proportion of trees damaged by wind for all species by size class is illustrated in Figure 1. In the unharvested reference plots, overstory trees were more or less evenly distributed among size classes, while proportionally more residual trees had larger diameters in the partially harvested plots. In both unharvested and partially harvested treatments, differences in the diameter distribution of total live trees vs. wind-damaged trees were not statistically significant ($p > 0.10$), suggesting that in this study neither harvest treatment nor tree size influenced the incidence or amount of wind damage.

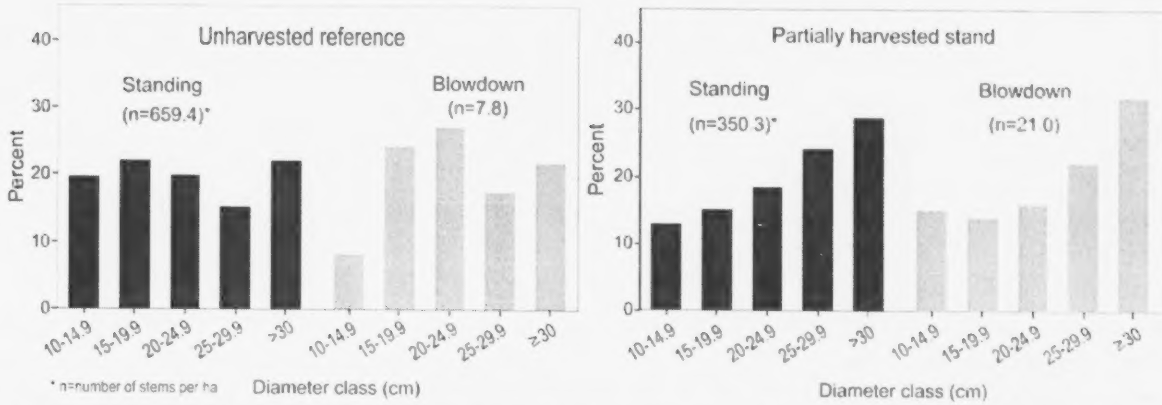

Figure 1. *Diameter distribution of postharvest residual and wind damaged trees in partially harvested and unharvested reference stand in northeastern Ontario. Area assessed: 9.53 ha in partially harvested and 15.70 ha in unharvested reference stand.*

The proportion of total live and wind damaged trembling aspen by diameter class and assessment year is shown in Figure 2. Trembling aspen was both the most common tree species and sustained the most wind damage in both partially harvested and unharvested treatments (Table 1). The highest proportion of undamaged trembling aspen were in the largest diameter class (>30 cm) for both treatments. In the 2003 and 2004 assessment periods, the highest proportion of damaged stems in the partially harvested plots were in the largest size classes, while in the unharvested plots damage was concentrated in the medium-sized trees (Figure 2). In 2005-06, the diameter distribution of damaged trees did not differ from that of total live trees (p >0.10).

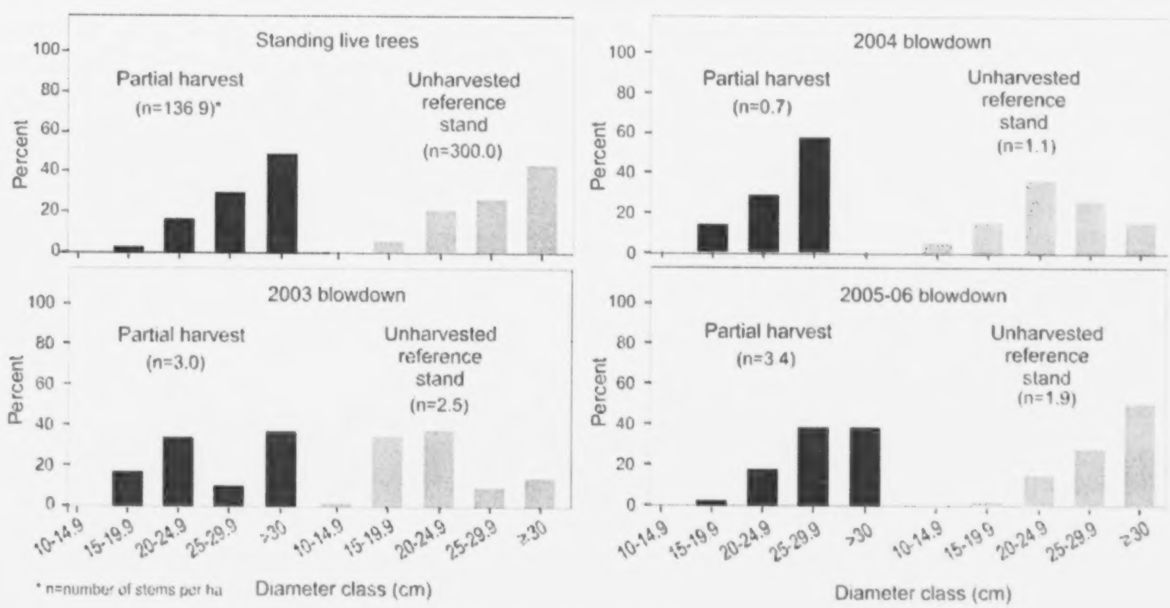

Figure 2. *Diameter distribution of postharvest residual and wind damaged aspen by assessment year and treatment in a partial harvesting study in northeastern Ontario. Area assessed: 9.53 ha in partially harvested stand and 15.70 ha in unharvested reference.*

Table 1. *Intensity (stems ha⁻¹) and percentage (in parentheses) of wind damaged trees by treatment and assessment year. (Note: Percentages for partial harvest treatments are based on post-harvest stem densities). Wind damage in partial harvest treatment results based on 9.53 ha sample plot area and unharvested treatment results based on 16.70 ha sample plot area.*

Spp.*	Partial harvest treatment						Unharvested reference				
	Pre-harvest overstory trees (stems ha^{-1})	Post-harvest residual trees (stems ha^{-1})	Wind damage (stems ha^{-1} (%))				Pre-harvest overstory trees (stems ha^{-1})	Wind damage (stems ha^{-1} (%))			
			2003	2004	2005-06	TOTAL		2003	2004	2005-06	TOTAL
AT	256.7	136.9	3.0 (2.2)	0.7 (0.5)	3.4 (2.5)	7.0 (5.1)	300.0	2.5 (0.8)	1.1 (0.4)	1.9 (0.6)	5.5 (1.8)
BW	256.7	136.9	2.0 (1.4)	0.7 (0.5)	0.8 (0.6)	3.5 (2.5)	243.8	0.2 (0.1)	0.1 (0)	0.3 (0.1)	0.6 (0.2)
FB	10.0	5.3	0.6 (11.2)	0.1 (2.0)	0.7 (13.0)	1.4 (27.0)	45.3	0.4 (0.9)	0 (0)	0.5 (1.1)	0.9 (2.0)
PB	6.0	3.2	0 (0)	0 (0)	0.2 (6.7)	0.2 (6.7)	6.3	0 (0)	0 (0)	0 (0)	0.0 (0.0)
PJ	85.6	45.7	1.2 (2.7)	1.3 (2.9)	3.1 (6.8)	5.7 (12.4)	3.1	0.1 (3.2)	0 (0)	0.1 (3.2)	0.2 (6.5)
SB	19.9	10.6	1.4 (13.6)	0.8 (7.5)	0.1 (1.0)	2.3 (22.1)	15.6	0.1 (0.6)	0.1 (0.6)	0.2 (1.3)	0.4 (2.6)
SW	21.9	11.7	0.3 (2.7)	0.3 (2.7)	0.2 (1.8)	0.9 (7.3)	45.3	0.1 (0.1)	0.1 (0.3)	0.1 (0.3)	0.3 (0.7)
All trees	656.8	350.3	8.6 (2.5)	3.9 (1.1)	8.5 (2.4)	21.0 (6.0)	659.4	3.4 (0.5)	1.4 (0.2)	3.0 (0.5)	7.8 (1.2)
Due to rounding errors, some rows and columns may not add to totals.											

* Species abbreviations: AT = trembling aspen, BW = white birch, FB = balsam fir, PB = balsam poplar, PJ = jack pine, SB = black spruce, SW = white spruce

The effect of wind on white birch, the species with the second highest number of wind damaged trees, is shown in Figure 3. Damage was equally distributed across all diameter classes but the largest proportion of damaged trees was in the smaller size classes. Again, much more white birch was damaged in the partially harvested plots than in the unharvested areas in the 4-year period (Table 1). Some of the damage may be attributed to post-logging decadence in white birch, which is known to exhibit dieback and decline symptoms within a few years of partial harvesting (Safford et al. 1990). Trees in this weakened state are more vulnerable to any damaging agent, including wind.

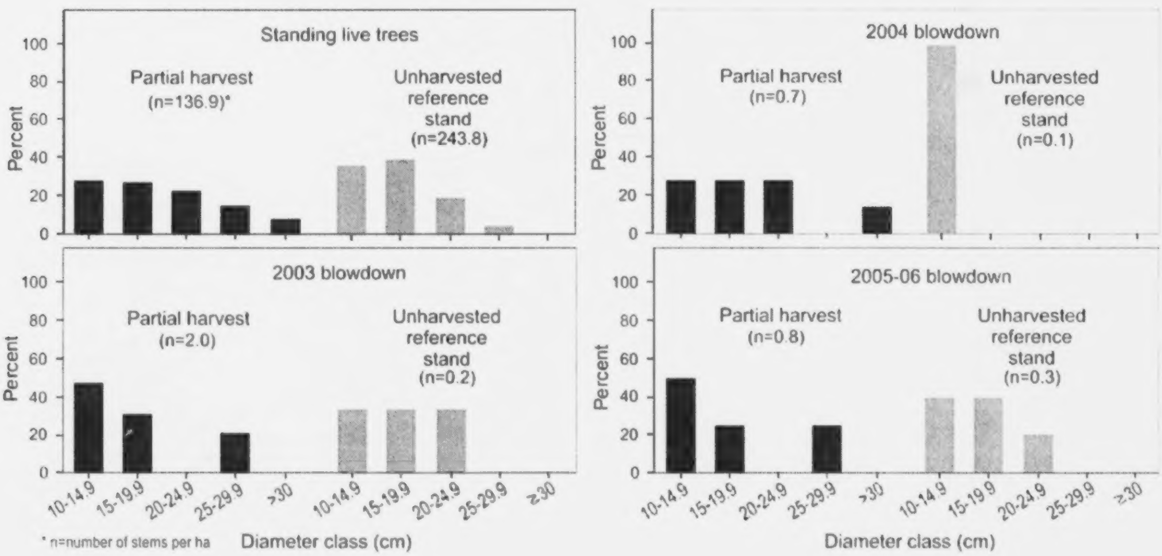

Figure 3. *Diameter distribution of postharvest residual and wind damaged white birch by assessment year and treatment in a partial harvesting study in northeastern Ontario. Area assessed: 9.53 ha in partially harvested and 15.70 ha in unharvested reference stand.*

The response of jack pine, which represents the conifer species with the largest number of wind damaged trees, is shown in Figure 4. Jack pine occurred predominantly in the partially harvested treatment plots (Table 1) and stems were mainly in the large size classes (>25 cm). In 2003 and 2004, damage occurred across the range of diameter classes. However, in 2005-06, wind damage occurred almost exclusively in the largest size classes. In the unharvested stands wind damage primarily affected stems in the smaller diameter classes (Figure 4), but due to the small initial number of jack pine in these plots these results are inconclusive.

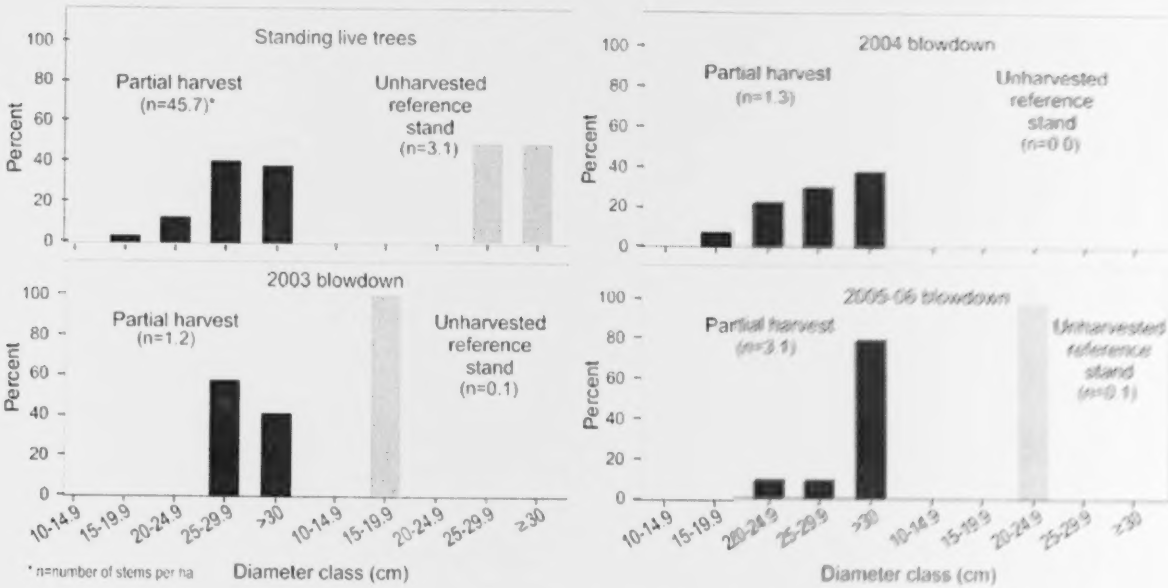

Figure 4. *Diameter distribution of postharvest residual and wind damaged jack pine by assessment year and treatment in a partial harvesting study in northeastern. Area assessed: 9.53 ha in partially harvested and 15.70 ha in unharvested reference stand.*

The higher number of residual trees of all species sustaining wind damage in the partially harvested plots (both in terms of stems ha^{-1} and percent of stems affected) compared to the unharvested reference stand ($p<0.05$) suggests that opening the stand left the residual stems vulnerable to wind damage.

Wind not only affected residual trees live at time of harvest, but also felled trees that were standing dead post-harvest (Table 2). In the partially harvested treatment plots, almost 30% of the dead trees that were standing post-harvest were knocked down, likely by wind, during the 4-year period, including almost a third of the trembling aspen, jack pine, and black spruce, and more than 13% of the white birch. In the unharvested reference plots, the numbers were also high, with over 40% of the dead trees falling, including two thirds of the trembling aspen, more than half the black spruce, and more than 10% of both white birch and balsam fir. Similar to results for total standing live trees, all species of dead trees were susceptible to wind. However, in both treatments the proportion of fallen dead trees increased from 2003 to 2004 and even more significantly in 2005-06 ($p<0.05$). The significant jump in number and proportion of fallen dead trees is likely due to the wind event in November 2005. Compared to live trees, more dead trees fell (p <0.05), contributing a larger proportion of the downed wood on the forest floor.

Table 2. *Intensity of wind damage (stems ha⁻¹) and percentage (in parentheses) of fallen dead trees by treatment and assessment year. (Percentages in the partial harvest treatment are based on post-harvest stem densities.) Results in partial harvest treatment based on 9.53 ha sample plot area and those in unharvested treatment on 16.70 ha sample plot area.*

Spp.*	Partial harvest treatment						Unharvested reference				
	Pre-harvest standing dead trees** (stems ha^{-1})	Post-harvest standing dead trees (stems ha^{-1})	Fallen dead trees (stems ha^{-1} (%))				Pre-harvest dead trees (stems ha^{-1})	Fallen dead trees (stems ha^{-1} (%))			
			2003	2004	2005-06	TOTAL		2003	2004	2005-06	TOTAL
AT	157.3	83.9	2.5 (2.9)	2.7 (3.2)	22.3 (26.6)	27.5 (32.7)	96.9	2.9 (3.0)	7.0 (7.2)	56.2 (58.0)	66.1 (68.2)
BW	57.3	30.6	0.3 (1.0)	0.8 (2.6)	3.1 (10.1)	4.2 (13.8)	82.8	0.1 (0.1)	2.2 (2.7)	8.4 (10.1	10.7 (12.9)
FB	0	0.0	0 (0)	0 (0)	0.2 (--)***	0.2 (--)	12.5	0.1 (0.8)	0 (0)	1.4 (11.2)	1.5 (12.0)
PB	0	0.0	0 (0)	0 (0)	0 (0)	0 (0)	0	0 (0)	0 (0)	0.5 (--)***	0.5 (--)
PJ	53.4	28.5	0.2 (0.7)	2.5 (8.6)	7.6 (26.6)	10.2 (36.0)	0	0 (0)	0.1 (0)	0.4 (--)***	0.4 (--)
SB	2	1.1	0 (0)	0.1 (10.0)	0.2 (19.9)	0.3 (29.9)	1.6	0.1 (6.3)	0.3 (18.8)	0.5 (31.3)	0.9 (56.3)
SW	0	0.0	0 (0)	0 (0)	0.1 (--)***	0.1 (--)	0	0 (0)	0.1 (--)***	0 (0)	0.1 (--)
All trees	270.0	144.4	3.0 (2.1)	6.0 (4.2)	33.5 (23.2)	42.6 (29.5)	193.7	3.2 (1.7)	9.7 (5.0)	67.5 (34.8)	81.0 (41.5)
Due to rounding errors, some rows and columns may not add to the totals.											

* Species abbreviations as per Table 1.
** Initial density of dead trees total is immediately post-harvest (2003).
*** Pre- and post-harvest densities (stems ha^{-1}) were estimated by sub-sampling the intensive measurement areas within treatment plots. Fallen trees were surveyed across the entire intensive measurement areas. Because of these sampling approaches, some species show no trees pre- or post-harvest (based on the sub-sample), but fallen trees were found (based on the complete sample of area).

Wind damage and tree rot

The number of wind damaged trees is summarized by treatment, incidence of visible rot, species, and year of damage in Table 3 and by species and diameter class in Table 4. Proportionally, wind damaged trees in the unharvested reference plots were almost three times as likely to contain rot as those in the partially harvested treatment plots (23.4% vs. 9.3%), suggesting that proportionally more healthy trees were affected by wind in the partially harvested plots. The dominant hardwood species on the study site (trembling aspen and white birch) had a higher proportion of damaged trees with rot in the unharvested reference plots while the dominant conifers (jack pine and black spruce) had a higher proportion of damaged trees with rot in the partially harvested plots. For all species combined for both treatments, only 15.4% of wind damaged trees contained visible rot (Table 4), suggesting rot was not a significant contributing factor to wind damage in this study.

Table 3. Number of wind damaged trees with and without visible rot by species and treatment assessed at a mixedwood partial harvesting study in northeastern Ontario.

Species*	Partial harvest treatment								
	2003		2004		2005-06		All years		
	rot	no rot	rot	no rot	rot	no rot	rot	no rot	% rot
AT	4	29	1	7	6	33	11	69	13.8
BW	1	19	2	7	2	8	5	34	12.8
FB	0	6	0	1	0	7	0	14	0.0
PB	0	0	0	0	1	2	1	2	33.3
PJ	2	12	0	13	1	30	3	55	5.2
SB	1	14	0	8	0	1	1	23	4.2
SW	0	3	0	3	0	2	0	8	0.0
All Species	8	83	3	39	10	83	21	205	9.3
% rot	8.8		7.1		10.8		9.3		
Species*	Unharvested reference stand								
	2003		2004		2005-06		All years		
	rot	no rot	rot	no rot	rot	no rot	rot	no rot	% rot
AT	18	42	9	19	2	31	29	92	24.0
BW	1	3	1	1	1	5	3	9	25.0
FB	4	7	0	0	1	9	5	16	23.8
PB	--	0	0	0	0	0	0	0	0.0
PJ	1	1	0	0	0	1	1	2	33.3
SB	0	2	0	2	0	3	0	7	0.0
SW	1	1	1	2	0	2	2	5	28.6
All Species	25	56	11	24	4	51	40	131	23.4
% rot	30.9		31.4		7.3		23.4		

Table 4. Number of wind damaged trees with and without visible rot by species and diameter class in a mixedwood partial harvest study in northeastern Ontario.

Species*	Diameter class/presence of rot												
	10-14.9 cm		15-19.9 cm		20-24.9 cm		25-29.9 cm		>30 cm		All Trees		
	rot	no rot	rot	no rot	rot	no rot	rot	no rot	rot	no rot	rot	no rot	% rot
AT	1	2	7	26	12	46	10	38	10	49	40	161	19.9
BW	5	19	1	13	2	4	0	6	1	1	9	43	17.3
FB	0	2	1	6	1	9	2	9	0	4	4	30	11.8
PB	--	--	--	--	--	--	--	--	1	2	1	2	33.3
PJ	--	--	1	3	1	6	0	14	2	34	4	57	6.6
SB	1	15	0	12	0	3	--	--	--	--	1	30	3.2
SW	1	4	0	1	0	1	1	2	0	5	2	13	13.3
All Trees	8	42	10	61	16	69	13	69	14	95	61	336	15.4
% rot	16.0		14.1		18.8		15.9		12.8		15.4		--

* Species abbreviations as per Table 1.

Wind damage and slenderness coefficient

Average slenderness coefficients (SC) for total live and wind damaged trees by species and assessment year are provided in Table 5. For wind damaged trees, SC varied among harvesting treatments, species, and assessment years. For the dominant tree species in the stand, the largest average SC was 0.938 for trembling aspen in the partially harvested plots in 2004. Statistically significant differences in SC between total live trees and wind damaged trees were not found among tree species or assessment periods.

Table 5. *The count and slenderness coefficients (SC) of total live and wind damaged trees by assessment year in a mixedwood partial harvest study in northeastern Ontario.*

Species		Total live trees	Wind damaged trees							
			Partial harvest treatment				Unharvested reference stand			
			2003	2004	2006	All Years	2003	2004	2006	All Years
AT	Count	321	35	7	33	75	36	19	31	86
	Avg SC	0.856	0.778	0.938	0.807	0.805	0.825	0.837	0.770	0.808
BW	Count	285	25	7	8	40	3	1	5	9
	Avg SC	0.959	0.923	0.927	0.838	0.906	0.850	1.000	0.817	0.848
FB	Count	34	3	1	7	11	6	0	9	15
	Avg SC	0.854	0.820	0.849	0.731	0.766	0.642		0.716	0.687
PB	Count	7	0	0	2	2	0	0	0	0
	Avg SC	0.608			0.620	0.620				
PJ	Count	45	14	13	30	57	1	0	1	2
	Avg SC	0.860	0.740	0.819	0.760	0.768	0.518		0.912	0.715
SB	Count	20	11	9	1	21	3	2	3	8
	Avg SC	0.849	0.853	0.824	0.716	0.834	1.024	0.857	0.888	0.931
SW	Count	40	4	3	2	9	1	2	2	5
	Avg SC	0.712	0.730	0.747	0.568	0.700	1.058	0.665	0.723	0.767
All Spp.	Count	752	92	40	83	215	50	24	51	125
	Avg SC	0.885	0.820	0.855	0.775	0.809	0.815	0.831	0.773	0.801

* Species abbreviations as per Table 1.

In Canada, guidelines for tree stability for wind damage based on SC have not been developed (Navratil 1995). This is due in part to the dearth of scientific studies on effects of wind damage on trees, as well as the many factors that influence wind damage, which makes it difficult to determine a single meaningful value. However, European studies focusing on Norway spruce indicate that after a thinning treatment, residual trees with a SC of less than 0.60 suffer no wind damage while trees with a coefficient greater than 1.00 have only a 10 to 15% survival rate (Navratil 1995). Navratil et al. (1994) believe that the SC thresholds from the European studies can be applied in Canadian forests. The work of Stathers et al. (1994) in British Columbia also supports European SC threshold values for tree stability. They suggested adopting thresholds of SC<0.60 for tree stability and SC>1.00 for instability in Canada.

Slenderness coefficients for mature trees from other parts of northern Ontario (OMNR 2003) and western Canada (Wang et al. 1998) are shown in Table 6. Comparing these to the results from this study indicates that, on average, trees at the study site have lower SC values than canopy trees on other sites in northern Ontario, and they are substantially less than those of trees in western Canada. These results may be attributed to differences in site and climatic conditions, as well as stand density and structure. The use of a SC of 1.00 as a threshold for instability, as suggested by Navratil et al. (1994) and Stathers et al. (1994), may need to be re-examined for trees in northern Ontario (see Tables 5 and 6).

***Table 6**. Average slenderness coefficients (SC) for mixedwood species in Ontario and western Canada (from OMNR 2003 and Wang et al. 1998).*

Species*	Ontario canopy trees **	Ontario sub-canopy trees **	Western Canada
AT	0.89	1.24	1.092
BW	0.86	1.29	N/A
FB	0.76	0.91	N/A
SB	0.81	0.97	0.937
SW	0.65	0.82	0.845

* Species abbreviations as per Table 1.

** Based on "canopy transition" successional stage (as defined in OMNR 2003)

Wind and direction of tree fall

Direction of fall of wind damaged trees is shown in Figure 5. In the first two years after the harvest treatment, trees fell in all directions, with most falling in a generally easterly direction. The largest percentage of trees in the partially harvested plots fell at 120 to 180° and damaged trees in the unharvested plots fell in all possible directions from 0 to 180°.

During the November 2005 wind event, an anemometer at the study site recorded the wind direction as being between 203 and 206°, i.e., from the SSW. The closest Environment Canada weather station at the Timmins, Ontario, airport recorded wind gusts from a direction of 210°. Most of the trees damaged in the final assessment period fell in the 0-60° and 60-120° direction, i.e., in alignment with the wind gusts. This suggests that most of the wind damage during this period resulted from the storm.

Study results suggest that most wind damaged trees fall in a predictable pattern based on the direction of the prevailing winds. However, a small number of trees fell in almost random directions, likely due to the effects of wind flow and eddies among tree crowns (Navratil 1995). Having trees fall in all directions creates many logistical problems. For example, it makes it difficult to re-enter the stand to salvage downed material or implement subsequent treatments. It also reduces the potential utilization of remaining wood.

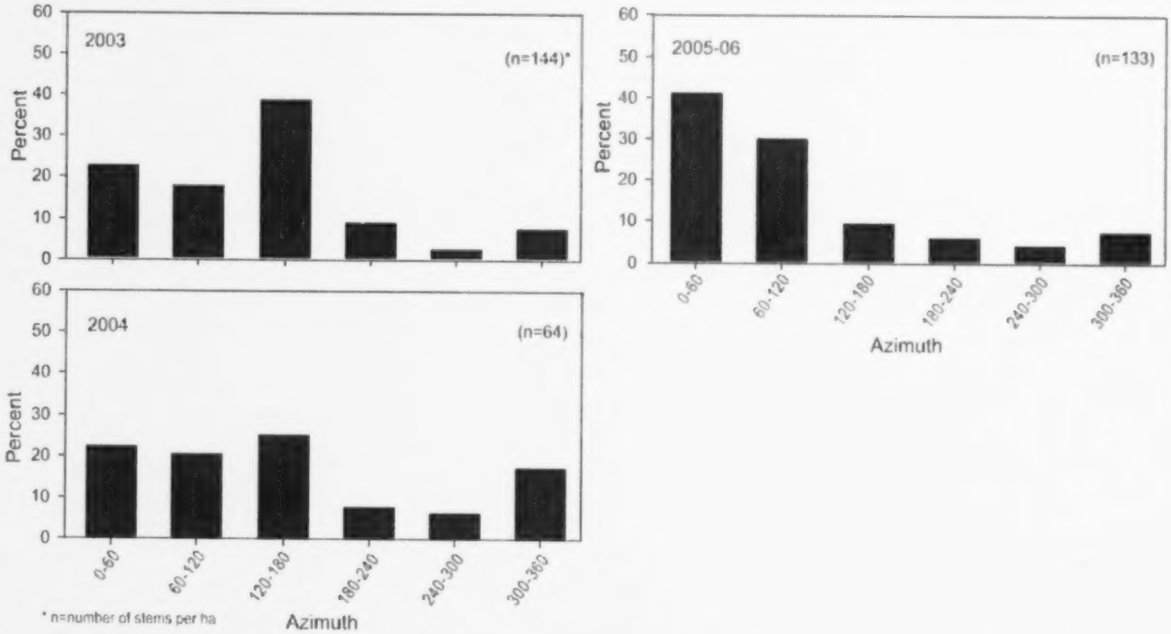

***Figure 5**. Direction of fall of wind damaged trees by assessment year in a partial harvesting study in northeastern Ontario.*

Wind damage effects and silvicultural objectives

Some wind damage was anticipated following the partial harvest treatments; however, more damage than expected occurred at this study site. While 5-year post-harvest assessments have shown that the natural hardwood and planted conifer regeneration have become established (Man et al. 2010), the long-term effects of the wind damage on the success of the silvicultural treatments will not be known for some time. The operational viability of removing the residual corridor as planned remains in question due both to the reduced amount of material available for harvest and the increased amount of downed material, which may cause logistical problems.

While the plan to remove the residual corridor remains in place, the stands have not yet reached the appropriate developmental stage to do so. The planned timeframe for removing the residual corridor in the partial harvest treatment was after conifer regeneration was established free from severe competition from regenerating hardwoods and shrubs. This was estimated to occur between 5 and 10 years post-harvest. If stand development continues as expected, the decision on how to proceed will need to be made sometime around 2013. Assessments of regeneration both in the harvested and unharvested corridors as well as additional wind damage to residual trees will continue. Analysis of these data will help to decide if and when removal of the residual corridors will occur. It will also help to identify the relative effects of wind on achieving silvicultural goals during the development of the new stand.

Summary and Conclusions

We assessed wind damage for 4 years following partial harvesting at the SLAM mixedwood study site east of Cochrane, Ontario. The percentage of damaged trees varied, with 6% of the residual trees in the partially harvested plots and 1.2% of residual trees in the unharvested reference plots affected. All species and sizes of trees were susceptible to wind damage. As well, a significant number of dead trees also fell. Within the first 4 years after harvesting 30% of dead trees in the partial harvest plots and over 40% of those in the unharvested reference plots were knocked down, likely by wind.

In this study we found that:

- Few live trees suffered wind damage during the first 4 years following harvesting but damage in the partially harvested plots was greater than that in the unharvested reference plots.
- Proportionally, more dead trees fell when compared to live trees, with differences greater in the unharvested reference plots.
- Wind damage occurred across the range of tree species present, but was more severe for trembling aspen, jack pine, and white birch, i.e., the three dominant species found in the study area.
- Wind damage was found during all 3 assessment periods covering the 4 years following harvest. The highest amount of damage in live trees occurred in the first year after harvest. For dead trees, most fell during the wind storm 4 years after harvest.
- More of the wind damaged trees in the unharvested reference plots contained some amount of visible rot in their stems compared to those in the partial harvest plots.
- Wind damaged trees with some amount of visible rot were found across the range of diameter size classes, with the percent of trees with rot similar across size classes.
- Slenderness coefficients calculated for damaged and undamaged (i.e., residual) trees were not significantly different. Average coefficients for damaged and undamaged trees were less than 1.00 for all species.
- Wind damaged trees fell in all directions. However, in 2003 and 2004, the predominant direction of tree fall aligned with the direction of the prevailing winds. In 2005-06, direction of fall was aligned primarily with the wind direction of one major wind event.

Overall, wind damage increased after partial harvesting. Compared to the unharvested reference plots, more residual trees were wind damaged and the proportion of healthy (without visible rot) trees damaged was higher. Other authors (Gardiner et al. 2005) have noted that strip cut systems (which are similar to the partial harvesting treatment in this study) make the remaining residual strips more vulnerable to wind damage. Essentially, each strip acts as a forest edge with increased vulnerability to wind damage. Results from this study support this conclusion.

The results also indicate that the slenderness coefficient, which is commonly used as an index to estimate tree stability, was not an effective indicator in these stands. We found no difference in slenderness coefficients between the total live and wind damaged trees. The use of the slenderness coefficient as an indicator of tree stability needs to be reviewed and possibly adjusted for Ontario forest conditions.

It remains too early to determine if the amount of wind damage sustained will affect whether the silvicultural objectives of the partial harvested treatment are achievable. If the conifer seedlings survive and grow at anticipated rates, and both the amount of viable standing material and market conditions justify the removal of the residual corridors, then the planned residual corridor removal will occur and the silvicultural objectives should be met. A decision on corridor removal was expected to be made between 5 and 10 years after planting (i.e., by 2013). Future monitoring will determine if and when that occurs.

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Appendix I. Stand Level Adaptive Management (SLAM) study treatment packages.

A brief description of the treatment packages used at the Abitibi study site in northeastern Ontario and relevant to the wind damage assessments (MacDonald et al. 2003).

Objective	Silvicultural treatments
Corridor mosaic with retention (use of partial harvesting)	Clearcut[1] 10-m-wide travel corridors[2], alternating with 10-m-wide unharvested corridors[2] Mechanically site prepared travel corridors in winter using a D8 tractor with an angle blade Plant conifers[3] (1500 per ha) at 2.0 m x 2.0 m spacing, in 6 rows across travel corridors No post-planting spray Clearcut residual corridors 5 to 10 years later (when conifers are well-established)
Unharvested reference stand (ecological control)	No treatments

[1]All harvesting operations were full-tree to roadside using feller-bunchers and grapple skidders during the late fall and early winter of 2002.

[2]Conifer and hardwood corridors (each 10 m wide) are permanently defined. Corridors were oriented north-south if possible to minimize wind damage following subsequent harvest entries and to equalize solar radiation across the regenerating conifer corridors. Partial harvesting objective uses corridor retention for the initial entry to inhibit aspen suckering and reduce the need for herbicides. In this case, travel corridors are clearcut, site prepared, and planted to conifers, while alternating unharvested corridors are allocated to hardwoods. The residual corridors are clearcut 5 to 10 years after the initial cut, when the planted conifers are tall enough to withstand competition from the subsequent aspen suckering.

[3]White spruce was planted based on the mill requirements of the forest company.

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